The Contribution of Brain Imaging to the Study of Human Language

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Abstract

This article presents an overview of the contribution of brain imaging techniques to the study of human language by first reviewing previous historical approaches to the study of the relationships between language and the brain. A brief introduction to modern brain imaging techniques follows, thereafter describing several concrete examples of contributions of these techniques to better know the human language, as well as to vivid debates into the linguistic and the psycholinguistic disciplines. This overview finishes with a comment on the present and the future of studying language with brain imaging techniques. It is concluded that these techniques are playing an essential role in the understanding of human language.

1. Introduction: Several landmarks in the study of language in the brain

Undeniably, language is inside the brain and is a product of the brain. Accordingly, neurobiology has traditionally been an important source of knowledge in the understanding of human language, both for a better description of the processes constituting the human language faculty, as much as for the relationships between them, their organization, and their interactions with other cognitive systems.

Starting with the studies by renowned pioneers on the relationships between brain and language in the 19th century (like Paul Broca and Karl Wernicke), neuroscience has contributed much to the study of human language. However, as usual in science, this knowledge has changed substantially throughout the years. Indeed, and for a long time, the main source of information that neuroscience has been able to employ in the understanding of the relationships between brain and language and, in turn, of language itself, has been the study of neurological patients suffering limitations on their linguistic processes after some kind of cerebral injury. This procedure presents two main limitations. One is that language is studied in damaged brains, that is, in artificially altered systems, so the information provided is useful mainly for the understanding of language in abnormal situations. The other is that lesions are never clearly limited to specific brain regions, so they may comprise wider or narrower areas than those of interest, i.e. those actually involved in specific linguistic processes and subprocesses. Given this situation, a

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precise description of the studied processes has always appeared misguided by a spatial non-specificity.

Despite this situation, several models of human language emerged from this type of data since the very beginning. An overview of these models reveals however that most of them approached language with a relatively naïve conception, and for that reason language was mainly divided into perceptive and productive processes (the former normally assigned to Wernicke's area, in the posterior and superior part of the left temporal lobe, the latter to Broca's area in the left inferior frontal gyrus), and their relationships with each other as well as with other cognitive processes. After decades of little or no advance, this early view was replaced by the bright contributions of Norman Geschwind in the 60's and 70's of the 20th century. Geschwind made a good attempt to provide a more detailed description of language and its processes, but still largely based on lesion studies. The main interest of the lesion data has been to better characterize the symptoms linked to concrete lesions, particularly with the aim of getting relatively accurate complete localizations of brain lesions, its prognosis and evolution of the symptoms, as well as determining clinical objectives for treatment and rehabilitation. Although these clinical aims might have contributed to a better understanding of human language, they have done so only marginally.

This state of affairs changed radically when brain imaging techniques became available. Most of the very first studies in the field, however, were performed without a complete and deep knowledge of the advances in linguistics or psycholinguistics. At this stage more intuitive than theory-based approaches appeared to be the rule. As a consequence, the contribution of brain imaging to linguistics – even to the understanding of language in general – was rather poor, the main interest consisting of localizing in the brain several processes presumably relevant for language. As an example, one of the most widely known studies at that time (Petersen, Fox, Posner, Mintun & Raichle 1988) separated language processes into hearing words, seeing (reading) words, speaking words, and thinking about words. The situation has changed substantially in later years, and linguistics has increasingly been used as a guide in the study of language in the brain. Further, the study of language in the brain has also become a guide in the study of linguistics. For a better comprehension of the current situation, first we need to briefly review the brain imaging techniques that are now available and the type of data which they provide.

2. Brain imaging techniques: An overview

Human language is substantiated by the activity of the human brain. Specific lesions of the brain affect language specifically, in such a way that language can be lost when certain brain cells (neurons) are damaged or disappear. This can be specific to certain language processes, that is, specific language processes are lost or affected when neurons located in certain places are affected. Accordingly, as language is based entirely on neuronal activity, knowing the latter is a suitable way to better understand language.

In the brain, the most important activity for our purposes is that of neurons. This is mainly a communicative activity, i.e. it is communication between neurons that basically constitutes brain activity. Neuronal communication is an electrochemical process, that is, neurons communicate between them by secreting a chemical substance, the neurotransmitter, which is captured by other neurons. In turn, the captured neurotransmitter causes electrical currents within the receiving neurons. These electrical currents may, in turn, produce other subsequent electrical currents within the receiving neurons, these causing the secretion of neurotransmitter to be captured by other (third) neurons.

Nowadays, at least two of these processes involved in neural communication can be measured in a non-invasive way. On one hand, electrical fields caused in the neurons receiving neurotransmitter can be detected externally; they reach the skin of the head, the scalp, and can be detected by electrodes placed on the skin itself. This is the foundation of Electroencephalography (EEG). Electrical fields develop with corresponding magnetic fields. The latter can travel outside the head and therefore be captured by magnetic sensors (SQUIDs: Superconducting Quantum Interference Devices) located even a few centimeters from the scalp. This is the underpinning for Magnetoencephalography (MEG). Both EEG and MEG can be termed as electromagnetic techniques.

On the other hand, when neurons secrete neurotransmitter, this process consumes high levels of energy. As a consequence, blood flow increases in the area of the brain where the chemical substance has been secreted, in order to carry on the extra doses of glucose necessary to replace the energy consumed. This increased blood flow can be detected externally by injecting a radioactive marker into the blood, so that an external device can detect the emitted radioactivity and determine the locus or loci of increased blood flow. This is the foundation of the Positron Emission Tomography (PET). The most preferred alternative, however, is to measure the local magnetic modifications produced by the increase in blood flow. This is done with a magnetometer, and is the foundation of the functional Magnetic Resonance Imaging (fMRI). Both PET and fMRI are hemodynamic techniques.

Blood flow is nevertheless a slow process. Hundreds of milliseconds are needed to increase the blood flow locally after the neurotransmitter has been secreted, and it takes some additional seconds for turning back to normal levels. As a consequence, hemodynamic techniques are excellent in localizing brain phenomena (in terms of millimeters), but fail to give us appropriate timing information of the neural processes. In contrast, electromagnetic techniques are excellent in measuring the timing of the neural processes (in terms of milliseconds), but fail at localizing precisely the neural origins of the recorded activity. The possibility that several neural sources are active simultaneously, as is usually the case, and considering that the number is normally unknown, obscures the spatial resolution of the electromagnetic techniques.

A more recent development is that brain blood flow can also be measured with near-infrared Optical Tomography, basically consisting of emitting light into the brain, at frequencies that can cross the skull and other tissues in between and reach the brain, then recording the amount of reflected light; the latter varies as a function of local blood flow. The spatial resolution of this technique, however, is low. Another recent development is the possibility to stimulate or inhibit local neural activity by interfering electric fields has become possible by means of applying a strong magnetic field to a given brain area at a specific point in time. This is again possible non-invasively, that is, without any kind of surgical preparation, since magnetic fields pass through any tissue between the stimulation device and the brain. Last, but not least, brain structure and anatomical connections can now be studied in detail thanks to magnetic resonance imaging without the functional option, a field improving day to day due to the availability of more powerful magnets. Although structural information may not appear as relevant as functional information provided by blood flow or electromagnetic activity for the study of such a dynamic process as language, many valuable data can be obtained about the main areas devoted to linguistic processes, their size, shape, and location, as well as their specific connections with other brain areas and circuits.

In the last decades, all of these techniques have contributed significantly to our understanding of human language, serving as a highly valuable tool providing information about the timing, the type, and the number of processes involved in language comprehension and production.

3. Brain imaging techniques in the study of language

A significant number of the contributions of brain imaging techniques to the study of human language have come from EEG, particularly when this technique is used to obtain the so-called Brain Event-Related Potentials, i.e. the specific reaction of the brain to a specific stimulus, obtained after averaging a number of EEG segments time-locked to the onset of stimuli of the same kind. The poor spatial resolution of EEG has not been an obstacle for valuable and relevant results; the reason is that, regardless of the real neural origin of the different fluctuations recorded in the scalp, two fluctuations with different topographical distributions in the scalp correspond to two different cognitive processes or subprocesses involved. With this rule, valid assumptions can be made when studying language, as well as any other cognitive process, with EEG. Thereafter, many of the processes or subprocesses identified with EEG can be spatially located in the brain more precisely by using hemodynamic techniques. This localizationist approach can in turn help to better identify commonalities between apparently different language processes or subprocesses, as well as between language processes and other, non-linguistic processes in the brain, contributing therefore to core debates about what language is, how it works, and its possible evolutionary origins.

In this regard, and as a good example of the contributions of brain imaging techniques to the study of human language, we will focus on one of the most vivid open debates in linguistics and psycholinguistics, i.e. the relationships between the three main components of language: phonology, syntax, and semantics. Particularly, many debates have focused largely around the relationships between the semantic and the syntactic components. Open questions are to which extent both influence each other, how and when do they interplay, and even if one can be the evolutionary origin of the other (normally, syntax from semantics). We will concentrate here on this semantics vs. syntax interplay debate.

As a first, now robust contribution of brain imaging with electromagnetic techniques to language, it can be asserted that syntax and semantics are clearly distinguished as two different entities in the brain. Accordingly, both terms, originally coined within the linguistic milieu are now substantiated and disentangled neurologically, as both types of operations cause distinct brain activity fluctuations across time, with notably different topographies.

As a matter of fact, brain imaging with electromagnetic techniques indicate that syntactic processes take place into two steps. One is reflected by an electrical negativity occurring between 150 and 250 milliseconds after the onset of a word. This time interval may vary, depending on the specific type of syntactic information being processed, and it appears that the analysis or detection of word category prevails in time over other syntactic features, such as morpho-syntactic aspects. The negative fluctuation reflecting a first syntactic analysis displays a frontal distribution, and is usually left-lateralized; for this reason, it is usually referred to as the Left Anterior Negativity (LAN). Its most plausible neural origin is in and around Broca's area, in the left inferior frontal regions of the brain, although other regions – such as the left temporal pole, the most anterior part of this lobe – seem to also contribute. Though procedural differences between experiments based on electrical activity and blood flow prevent a total confidence when identifying the neural origin of the LAN, most of the evidence supports these neural origins. A relevant result is that this first syntactic analysis has been seen to be automatic, i.e. it occurs even when the subjects are performing tasks other than the linguistic task in progress. As can be seen, a better and more complete definition and understanding of the language processes emerges with this type of data.

At about the same time, semantic analyses seem to start. In this regard, however, a temporal prevalence of syntactic over semantic analyses has usually been supported, as the latter seem to appear some time later than the former. This is not a closed debate, however, and semantic activity certainly can be observed around 250 milliseconds after stimulus onset, or earlier. However, when semantic information refers to the sentence in progress, it is true that the most reliable and replicated result is a negativity around 400 milliseconds, the N400. With a parietal distribution, this is a good example of the caution with which one has to interpret EEG or MEG results, as the origin of this negativity seems to be at the very bottom of the pole of the temporal lobe, as has been elucidated by means of intra-cerebral recordings in epileptic patients. Whatever the case, this semantic-related brain activity usually appears later than the one related to the first syntactic analyses, it is less automatic, and it is not rare that it can be affected by the results of the first syntactic analyses. In this regard, when the first syntactic processing determines that the word is (syntactically) incorrect, no subsequent semantic analyses take place, at least under certain circumstances. This would indicate not only a temporal prevalence of syntax over semantics, but also a hierarchical relationship between both types of processes.

Whereas first-pass syntactic parsing – reflected by the LAN – seems a specifically linguistic brain process, semantic integration analysis – reflected by the N400 – does not appear to belong exclusively to language, in a strict sense. The N400 has been reported for other than linguistic stimuli, such as pictures, music pieces, faces, and so on, whereas the LAN has not been reported for other than linguistic syntactic processes. This kind of information is relevant to better characterize both linguistic components. In this regard, brain imaging supports not only that syntax and semantics are indeed two distinct processes in the brain, differing both in time and topography (or neural origin), but also that both types of phenomena can be influenced differentially and pertain to different types of information. Hence, whereas semantic processes could be related more directly with the interactions between the individual and her surrounding world – thus sharing functions with, among others, perceptual and motor processes – syntax appears as an encapsulated (i.e. it cannot be affected by other processes) computational module with a concrete function, mostly, if not exclusively, devoted to language. This depiction, although evolved from some classical proposals in linguistics (e.g. Chomsky 1965), is based on such an objective evidence as brain activity, and clearly contributes to a better and more solid understanding of human language. Even though the description of the nature of syntactic and semantic processes outlined above corresponds to relatively regular situations, there are circumstances in which the description of the interplay between syntax and semantics described earlier would not apply. Brain activity has also shown that linguistic processes can behave differently under a number of circumstances, so that even syntax can be affected by semantics (e.g. Martín-Loeches, Nigbur, Casado, Hohlfeld & Sommer 2006). These particularities have to be taken into consideration if we want to better describe human language in depth.

But we mentioned above that syntactic processes develop in two steps. After the first-pass parsing syntactic analysis and consecutive to semantic integration, a large positive deflection of brain activity appears at about 600-800 milliseconds. This component, the so-called P600, appears to reflect the final understanding of a sentence (or of the portion of the sentence read so far), a final step that is syntactical in nature, as it primarily refers to the structure of the sentence. Brain activity also supports, nevertheless, that this final composition of the sentence structure is highly a function of both the semantic and the syntactic sources of information, although the latter would play a more relevant role. This final syntactic step also appears to take place far from the first syntactic processes, in terms of brain anatomy. Parietal and temporal areas of the brain seem to contribute significantly to the processes reflected by the P600, but in any case (and given their different topography) they seem to be different from the earlier syntactic processes reflected by the LAN. In fact, it is also possible that the last syntactic processes reflected by the P600 are not as language-specific as the first-pass processes, as this brain fluctuation has also been reported for several other cognitive operations such as music, arithmetic, and even logical sequences of pictures. Accordingly, the processes involved in reaching a conclusion about the structure of a sentence could be part of a general-purpose brain device to determine structures in many other domains. Again, this depiction has to be considered when attempting to understand human language in detail.

Auditory aspects of language, such as phonology o prosody, have been less studied with brain imaging techniques. The reasons for this are unclear, although it might be a possible consequence of a traditionally scarce attention in linguistics to these aspects, probably in turn a consequence of considering them as less relevant or crucial for human language (e.g. Hauser, Chomsky & Fitch 2002). Brain imaging has shown that phonological information may be processed as soon as at about 150 milliseconds after stimulus onset, or earlier, that this is an automatic process and that it seems to occur not only in specialized areas of the brain surrounding primary auditory areas, but also – as predicted some time ago by the Motor Theory of Speech Perception (Lieberman & Mattingly 1986) – in the motor portions of the cerebral cortex specialized in producing these sounds by the hearer herself. Brain imaging substantiates therefore that hearing and producing language occur in unison, as a useful mechanism to obviate differences in pronunciation and vocalizing frequencies to better recognize speech sounds whatever their source.

Of course, many other language processes can be studied by means of brain imaging techniques, but we can only bring here some of the main examples. As a last one we can mention the studies of discourse processing with both electromagnetic and hemodynamic techniques. These two ways to approach brain activity converge in the presence of several specific processes beyond the word and the sentence level involved in language processing. Interestingly, many of these data are also contributing to a strong debate in psycholinguistics about the nature of language itself. In the end, this debate seems to relate to the conception of language processes as abstract processes or, instead, as pertaining to general cognition processes based on the interactions between the individuals and their environments. Namely, the debate is whether understanding a linguistic message is an embodied process, by virtue of which reading or hearing language necessarily implies the mental revival of the described situation as if it were actually perceived or performed, or whether the final understanding of language remits to an abstract code that can be (but is not necessarily) transformed into an embodied representation of the situation. This debate is still open, though evidence for the embodied representation at these levels of language processing have been growing in recent years (Martín-Loeches, Casado, Hernández-Tamames & Álvarez-Linera 2008).

4. The present and the future of brain imaging in the study of language

Some of the hottest current debates in linguistics and psycholinguistics have been exposed in the previous section. However, brain imaging is a permanently growing field. This means that more facilities are continuously being available, with a clear trend towards measuring brain activity in more valid and natural situations, as well as in populations for which brain imaging has traditionally been difficult. In this regard, it is remarkable that new techniques such as the near-infrared optical tomography can be used in newborns and very small children, since these techniques are not only non-invasive, but also much more comfortable for the subjects than previous options. Thanks to this situation, newborns have been studied in regards to the selective reactions of their brains to linguistic parameters. It has been seen, for example, that newborns can distinguish the sounds and phonemes of their mother language from other languages, as a consequence of their exposition to these specific sounds in-uterus (Peña, Maki, Kovačić, Dehaene-Lambertz, Koizumi, Bouquet & Mehler 2003). These types of results are relevant not only to understand language development, but also to better understand human adaptations for language and, therefore, the possible evolutionary origins of this extraordinary human faculty. A wide horizon of future explorations is now open thanks to brain imaging.

In fact, studying brain activity can directly contribute to interesting open questions on the origins of language. In this regard, several recent experiments have explored the differences between processing syntactic structures that can be afforded by non-human primates, such as the finite state syntax, and the specifically human phrase structure grammar. Results show that the latter implies more extensive portions of the same neural tissue used to process the former (Friederici, Bahlmann, Heim, Schubotz & Anwander 2006). This kind of data provides clues not only for the origins and evolution of language but, in turn, to better define the nature and quality of the linguistic processes of interest.

As mentioned in the previous section, brain imaging techniques are helping us in creating a solid depiction of what language is, what it is composed of, and the interactions and relationships between its different components and subcomponents, as well as their relationships to other non-linguistic features. Although some general rules emerge, it is also true that the picture painted by brain imaging techniques is complicated with many particularities in which the general trends do not apply or function differently, something that has to be taken into consideration if we want to better understand what language is and how it works.

In sum, the contribution of brain imaging to the study of language is an important one and, strikingly, it is actually starting now. Thanks to these techniques, a wide number of new research fields in linguistics and psycholinguistics are now open. Brain imaging is contributing and will contribute importantly to the study of human language.

Several authors are proposing linguistic and psycholinguistic models of human language based on behavioral experimental evidence, but largely and significantly guided by brain imaging data (e.g. Townsend & Bever 2001 for a concrete example relative to sentence processing, Ullman 2004 for a more comprehensive model of language, or Friederici & Wartenburger 2010 for a recent review in this regard). In our view, this is the most acceptable situation. Theorizing about language is necessary, and behavioral (and even introspective) data have been largely used, and even appear necessary. But brain activity constitutes robust and objective data aiding significantly to better test proposals and theories on human language. In this sense, brain imaging techniques are just another tool, not the solution to solve debates in linguistics or psycholinguistics. But this tool is scientifically so powerful that it must be known and taken into consideration as probably one of the best approaches currently available to understand human language.

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